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Microstructural Effects on Grinding of Alumina and Glass-Ceramics

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Grinding forces were measured in aluminas and glass-ceramics with various microstructures. The microstructures were found to exert a profound influence on the machinability. In particular, the controlling toughness variable is that which pertains to small cracks, not that conventionally measured in a large-scale fracture specimen.

IT IS well documented that the principal material variable in microfracture-controlled properties of brittle ceramics, such as erosion, wear, and machining, is the "toughness."[1] This is in accord with intuition: the greater the resistance to fracture, the harder it should be to remove material in localized, cumulative, surface contact processes. Implicit in existing material removal theories is the presumption that toughness is a single-valued quantity for a given material. Recent studies of the fracture properties of a wide range of ceramics call this presumption into serious question; toughness is generally *not* a material constant, but rather some increasing function of crack size (*R* curve, or *T* curve).[2] In certain aluminas, for example, the toughness can increase by a factor of 3 or so, depending on the microstructure.[3,4] The *T*-curve effect is seen most strongly in aluminas with larger grain sizes and lower contents of grain-boundary glassy phase. Most notably, the *T* curves for different aluminas tend to cross each other,[4] so that the toughness rankings at large and small crack sizes appear to be reversed. Clearly, if we wish to retain toughness as an indicator of wear resistance, we need to qualify the scale on which this parameter is determined. Indeed, such a need was foreshadowed in an earlier experimental study on the erosion resistance of ceramic materials by Wiederhorn and Hockey.[5]

Accordingly, surface grinding tests were made on selected ceramic materials for which well-characterized *T*-curve data are available. The primary materials were aluminas from a previous study,[4] where the resistance characteristics were determined from the strengths of specimens containing indentation flaws.* In addition, two commercial glass-ceramics were tested. A subsequent quantitative analysis of the indentation-strength data has provided upper (large crack size) and lower (small crack size) bounds, T_∞ and T_0, to the T curves for these materials.[6] Table I lists these parameters for comparison with the grinding results.

The grinding forces were measured using a dynamometer on the table of a surface grinding machine. Runs were made at fixed depths of cut, 5, 10, 15, and 20 μm, using a 240-grit diamond wheel (width 10 mm), rotating at 3300 rpm with a horizontal feed rate of 16 mm·s^{-1} and with water-soluble oil lubrication. The conditions of our experiments were such that the scale of individual damage events was always much smaller than the depths of cut. The specimens were first cut into bars 5 mm wide and then mounted in a row on the dynamometer so that force measurements could be made on all materials in a single pass. The results are plotted in Fig. 1. Note from the relative positions of the curves that the aluminas and glass-ceramics have been ranked in order of diminishing grinding resistance in Table I.

It is immediately apparent from Fig. 1 that different aluminas and different glass-ceramics can vary widely in their grinding resistance. Thus the alumina with the highest resistance in Table I (i.e., AD90) is that with the greatest glass content. This result may come as no surprise to those who prepare ceramic powders by ball milling: alumina spheres with high glass content are found to be far more durable than similar high-purity spheres.[7] Note also from Table I that for aluminas of comparable purity those with higher grinding resistance have finer grain sizes (cf. A999 and Vistal). Most interesting, however, is the quantitative correlation between grinding resistance and toughness parameters. The macroscopic toughness T_∞ (i.e., the toughness K_{IC} we measure in conventional large-scale fracture tests) actually shows an *inverse* correlation with the grinding resistance. On the other hand, the microscopic toughness T_0 does appear to scale in the right direction. The implication here, of course, is that the grinding damage process is determined at the scale of the microstructure. The data for the two glass-ceramics in Table I serve to reinforce the point; on the basis of the T_∞ values we would be unable to choose between the two materials, whereas the relative values of T_0 confirm Macor (specified as a machinable glass-ceramic by its manufacturer) as the material of lower grinding resistance.

We conclude, therefore, that the time-honored conception of "toughness" as a universal indicator of superior mechanical properties, at least on the microscale, needs to be carefully qualified. The use of conventional fracture toughness evaluations to predict resistance to wear, erosion, and machining may lead to imprudent choices of materials for structural applications. On the positive side, a more complete understanding of the micromechanics that determine the complete crack resistance curve may ultimately help us optimize microstructural elements (glass content, grain size, etc.) for minimum surface degradation.

Table I. Comparison of Toughness and Grinding Resistance Parameters*

Material		Additive (%)	Grain size (μm)	T_∞ (MPa·m$^{1/2}$)	T_0 (MPa·m$^{1/2}$)
Alumina	AD90†	10	4	3.2	2.8
	Sapphire‡			3.1	3.1
	AD96†	4	11	2.9	2.2
	AD999†	0.1	3	4.3	2.2
	Vistal I†	0.1	20	4.1	1.7
	Vistal II†	0.1	40	4.6	1.5
Glass-ceramic	Pyroceram§		1.5	2.3	2.0
	Macor§		13	2.3	1.0

*T_∞ and T_0 evaluated from indentation-strength data (Ref. 5). Material rankings in order of decreasing resistance (from Fig. 1). †Coors Porcelain Co., Golden, CO. ‡Adolf Meller Co., Providence, RI. §Corning Glass Co., Corning, NY.

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*Only those materials originally available in disk form in that earlier work were selected. The strength data for these specimens are not limited by edge failures, so the resistance characteristics are more likely to reflect the intrinsic microstructural influence (Ref. 4).

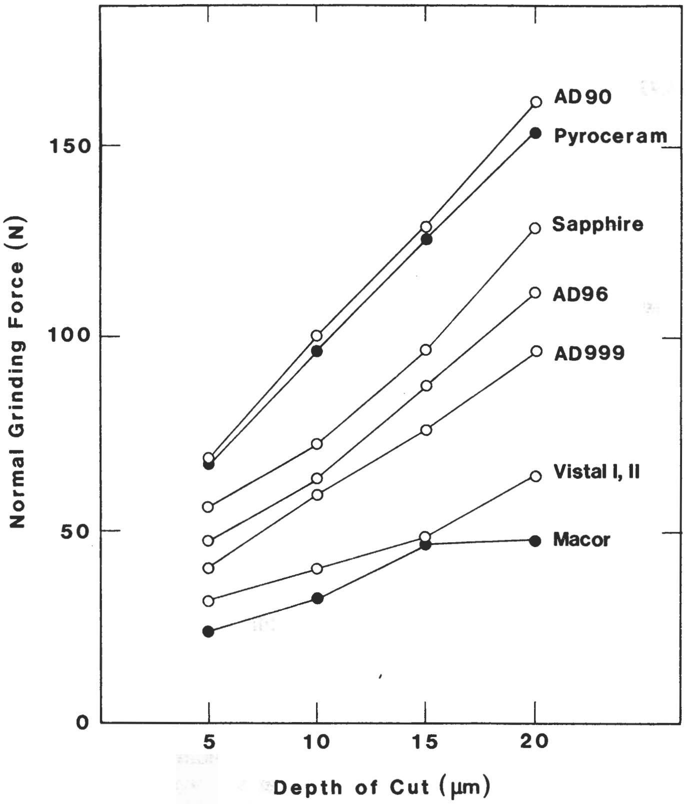

Fig. 1. Vertical grinding forces as function of depth of cut. Open symbols represent aluminas; closed symbols represent glass ceramics.

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